SKIN TEMPERATURE RESPONSE OF THE FOOT UNDER HOT ENVIRONMENTAL CONDITIONS

by

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INTRODUCTION

The fact that the extremities have great importance in thermo regulation of the human body is well established. The skin temperature and consequently the heat loss is influenced by the temperature and the flow of the blood and the surrounding air temperature.

The temperature of the blood flowing in the limb is by no means either uniform or constant. Fluctuation of blood flow in the foot of a subject exposed, during one day, to a hot environment is very large (commonly amounting to 100%).

It is well known that the effective insulation of the air to heat flow is less for cylinders of small diameters than those for large diameters. It is also less for spheres and cylinders than for flat surfaces. A rise in skin temperature of the toe and foot therefore is more effective in promoting heat loss than a similar change in temperature of other larger and flatter areas.

The foot and toes can be considered as a series of cylinders with the toes having approximately 15% of the entire surface area. The effect of curvature is such that, with an equal temperature gradient from the skin to the air, more heat must be lost from the toe than from a comparable area of the rest of the foot. The existence of these curved areas in the foot is particularly useful in regulating heat loss. This regulation is aided by the increased convection generated in the air as heat loss increases, because the increased convection further decreases the insulation effect of the air.

It has been estimated that the foot, which has 9% of the total body area, loses 6.5% of the total heat in a hot environment and only 3.5% of the total heat in a cold environment.

Under conditions of extremely still air, the heat loss by non-evaporative modes (radiation and convection), is a function of temperature difference between the skin and the air temperature.

Hence, the skin temperature and the air temperature are sometimes sufficient to calculate the non-evaporative heat transfer. Also, it has been established experimentally that there is a close relation between the skin temperature of the foot and the human comfort below the evaporative cooling zone.

The object of this report is to study experimentally the skin temperature response of the foot under hot environmental conditions. The effect of clothing was also considered in these experiments, since the foot has a particular value for students of clothing.

LITERATURE REVIEW

Several papers have appeared in literature on the subject of this report. Bazett et al. (1) and Love (5) studied the thermal exchange of the bare foot when exposed to hot environments for long periods of time. They also showed that the temperature of the blood in transit in the limb is not uniform or constant and the fluctuation in the blood flow is very large.

Bazett et al. (2) also carried out experiments on bare and booted foot exposed locally to a low temperature (as low as -25°F). They found

that the skin temperature and heat loss from the foot decrease rapidly. The heat capacity of clothing and tissues was considered in these investigations.

Chenko (4) showed that the feeling of discomfort is closely associated with the floor surface temperature and with the temperature of the skin of the sole of the foot.

This report presents the results of an experimental investigation conducted to study the skin temperature response of the foot when exposed locally to hot environments. The foot was bare, with socks, and with socks and shoes. The temperature responses of the foot have been taken by placing the foot on a hot plate at various temperatures for periods of 30 minutes. Another experiment was conducted by inserting the foot in a special wooden enclosure inside which air could be maintained at various temperatures (90, 100, 110, 120°F). The feeling of warmth and hotness has been recorded while increasing the oven or plate temperature.

EXPERIMENTAL PROCEDURE

Four different experiments were carried out and are outlined as follows:

1. The first of these experiments was performed on two different subjects. Each subject sat in an office chair with his feet resting on a hot plate whose temperature could be adjusted before contacting the foot. Four temperatures were used for the plate, namely 90, 100, 110, 120°F.

2. The second of these experiments was performed with one subject. The foot was subjected to still warm air by placing it inside a wooden chamber. In this chamber, the temperature of still air could be controlled.

3. The third set of experiments was similar to the first except that the foot with the three conditions (bare, with socks, and with socks and shoes) was placed on a hot plate which initially had a temperature equal to the room temperature. Then the plate temperature was increased gradually until the subject felt that his foot was warm. A gradual increase in the plate temperature was continued until the subject reported a feeling of hotness, and then the plate temperature was decreased gradually until the subject resumes the feeling of comfort. One subject was used for this series of tests.

4. In the last set of experiments the foot was inserted inside the warm air chamber and the air temperature was increased until the feeling of warmth in the foot was reported. Then the air temperature was increased until the subject felt that his foot was too hot. Then the air temperature was decreased gradually until the feeling of warmth was reported again.

In the above-mentioned experiments, the skin temperature of the foot was recorded at 4 locations every 40 seconds for each location over a total period of 30 minutes.

Experimental Apparatus

The experimental arrangement for the first set of experiments is shown in Fig. 1. It consisted of a plate with an embedded heating coil. A 24-gauge copper-constantan thermocouple with its junction attached to the plate was connected to a sensitive galvanometer for fast manual control of the plate temperature.

The arrangement for the second set of the experiments is shown in Fig. 2. A special wooden chamber was used with two suspended thermocouples to record air temperature for manual control. A sheet of cork board was placed between the heater and the rest of the chamber to decrease the heat gain to the foot by radiation. The subject was seated in an office chair. The temperature of the chamber was adjusted by varying the current input to the electric heater through a variable transformer.

For all experiments, the locations of the thermocouples on the foot were:

1. the sole
2. the heel
3. the top front of the foot
4. the ankle

Skin Temperature Measurements

Skin temperatures were obtained with 24-gauge copper-constantan thermocouples. The thermocouple junctions were held on the skin by scotch tape.

The thermocouples were connected to a multi-point recorder.

The temperature measuring system consisted of:

1. The thermocouples as the primary elements.

2. A self-balancing potentiometer which measured the unknown e.m.f. by balancing it against em.f. read out from a position of the contactor on a calibrated slide wire.

3. A voltage and power amplifier.

4. A motor to move the pointer to indicate the temperature.

5. A print wheel carriage attached to the pointer to print the temperature of each point every 40 seconds.

EXPERIMENTAL RESULTS

Figures 3 to 6 show the skin temperature changes with time for locations (1) and (2) for the first set of the experiments. It was noticed that:

1. When contacting the bare foot or the foot with socks with the hot plate, a sudden increase in temperature of the skin of the foot at the bottom occurred. The skin temperature increased as the plate temperature increased.

2. Very large fluctuation in skin temperature in contact with the plate whose temperature was 100°F or more. The maximum skin temperature of the bare foot or with socks was 110°F.

3. The temperature of the foot differed from one position to another. The temperature was higher finally at the heel than at the sole. The final average temperature of the foot was given in Table I for the hot plate case for locations (1) and (2).

TABLE I

Average final temperature of skin of the foot in contact with a hot plate between the two subjects

		Plate Temperature, F							
		90		100		110		120	
Thermocouple Location		1	2	1	2	1	2	1	2
Foot Covering	Bare	96	96	102	105	103	106	105	107
	With Socks	96	96	103	103	105	106	105	105
	With Shoes	96	--	99	--	101	--	101	--

Location: 1 = the sole; 2 = the heel.

Figures 7 through 11 show the skin temperature change with time for the four locations on the foot as determined by the second set of experiments. The following observations could be mentioned:

1. By inserting the foot in the hot chamber, the temperature variation with time curve can be divided into two zones:

   a. The first zone, in which the temperature increases at a high rate. This can be considered as the non-evaporative zone.

   b. The second zone in which no or a very small increase in temperature occurred. This can be called the active sweating zone, owing to cooling by evaporation of perspiration. No significant fluctuation in skin temperature was observed. Maximum instantaneous temperature attained was 110°F.

2. The temperature distribution of the skin of the foot was almost uniform.

3. The final average temperatures of the skin of the foot (the arithmetic mean) are given in Table II.

TABLE II

Arithmetic mean of final skin temperature of foot inserted in warm chamber

Temperature of the Chamber, F		90	100	110	120
Condition of the foot	Bare	94	96	99	99
	With Socks	95	96	98	98
	With Shoes	93	96	98	98

The feeling of warmth or hotness of the foot in contact with the hot plate was recorded in the third set of experiments with the following results:

1. The foot feels warm all over the bottom of the foot; at the same time the temperatures at different locations over the bottom of the foot were very nearly identical.

2. As the plate temperature increased, the foot temperature at the heel increased more rapidly than the temperature at other parts, and the foot felt hot at the heel before the other parts of the foot felt hot.

3. The feeling of "too hot" was attained at higher temperature when the foot was bare rather than when the foot was in socks.

4. When enclosed by sock and shoe, the foot did not feel too hot when the plate temperature increased up to 120°F.

5. Table III gives the foot temperature at two locations (1) and (2) when the foot, foot and sock, or foot, sock and shoe was in contact with the hot plate and the foot felt warm or hot.

The fourth set of experiments showed the following results:

1. By inserting the foot in the wooden box and gradually increasing the temperature of the air in the box up to 150°F, the subject did not report that he felt too hot at all.

2. Maximum temperature of the skin attained during this experiment was as follows:

a. 103.5°F. with bare foot

b. 105 with foot with socks

c. 101 with foot with socks and shoe

3. Table IV gives the arithmetic mean of the foot temperature of the four locations when the foot felt warm.

TABLE III

The temperature of the foot at two locations (1) and (2) contacting the hot plate

Foot Condition	Foot Feeling	Plate Temperature	Foot Temperature, F	
			location (1)	location (2)
bare	*(1) feeling warm	97	100	100
	*(2) feel hot	113	105	109
	*(3) feel warm again	103	102	102
with socks	(1) feel warm	100	101	102
	(2) feel hot	107	102	106
	(3) feel warm again	104	102	105
with shoes	(1) feel warm	110	101	102
	(2) feel hot	120	-	-
	(3) feel warm again	-	-	-

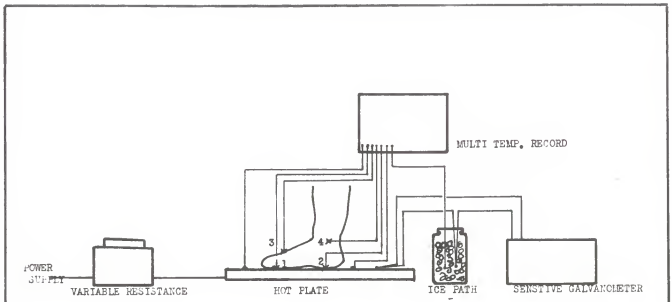
* From (1) to (2) the temperature of the plate increases gradually.

* From (2) to (3) the temperature of the foot decreases gradually.

TABLE IV

Average temperature of the foot when a feeling of warmth was reported. Foot inserted in an insulated box

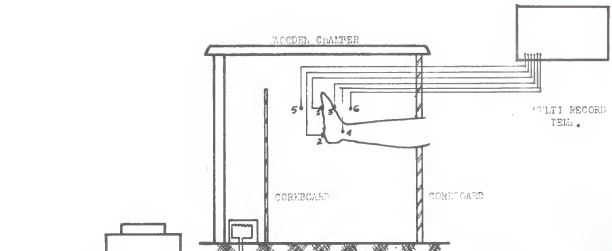
Foot Condition	Average Skin Temperature, ^{o}F	Temperature of the Chamber, ^{o}F
Bare	97	132
With Socks	101	135
With Shoes	97	130



ARRANGEMENT FOR THE FIRST SET OF THE EXPERIMENTS
SHOWING THE THERMO-COUPLES LOCATIONS ON FOOT AND
THEIR CONNECTION

FIG (1)

FIG. (2)



THE FOOT IN THE WOODEN CHAMBER SHOWING
THE LOCATION OF THE THERMO-COUPLES

FIG. (3)
SUBJECT (1) A

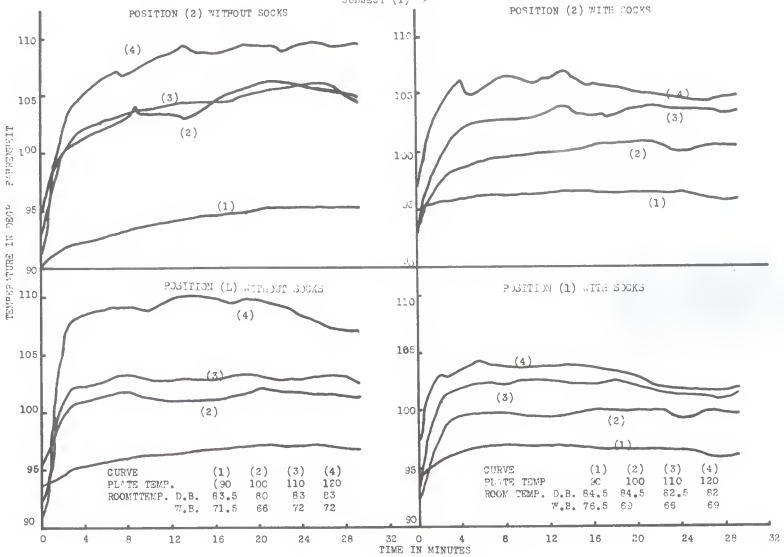

POSITION (2) WITHOUT SOCKS
POSITION (2) WITH SOCKS
POSITION (1) WITHOUT SOCKS
POSITION (1) WITH SOCKS
TEMPERATURE IN DEGS. FAHRENHEIT
TIME IN MINUTES
(1)
(2)
(3)
(4)
CURVE (1) (2) (3) (4)
PLATE TEMP. (90 100 110 120
ROOMTTEMP. D.B. 83.5 80 83 83
W.B. 71.5 66 72 72
CURVE (1) (2) (3) (4)
PLATE TEMP 90 100 110 120
ROOM TEMP. D.B. 84.5 84.5 82.5 82
W.B. 76.5 69 66 69

FIG. (4)
SUBJECT (1) B

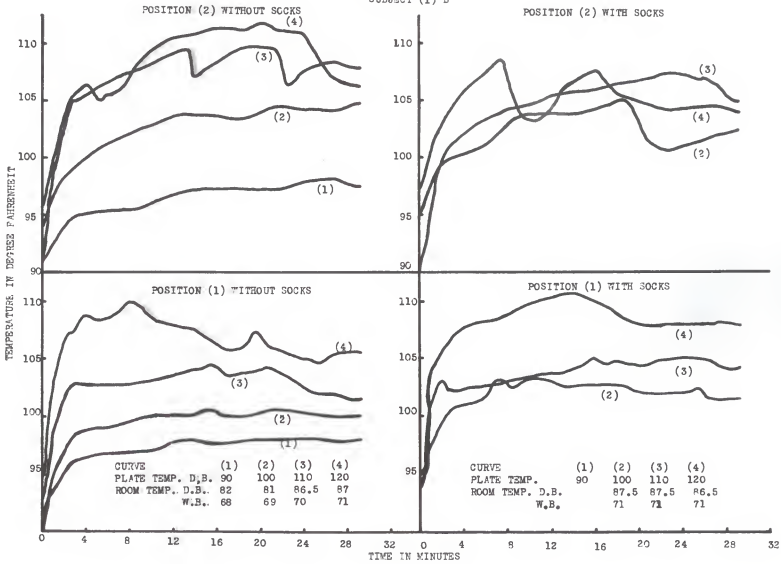

POSITION (2) WITHOUT SOCKS
POSITION (2) WITH SOCKS
POSITION (1) WITHOUT SOCKS
POSITION (1) WITH SOCKS
TEMPERATURE IN DEGREES FAHRENHEIT
TIME IN MINUTES
CURVE (1) (2) (3) (4)
PLATE TEMP. D.B. 90 100 110 120
ROOM TEMP. D.B. 82 81 86.5 87
W.B. 68 69 70 71
CURVE (1) (2) (3) (4)
PLATE TEMP. 90 100 110 120
ROOM TEMP. D.B. 87.5 87.5 86.5
W.B. 71 71 71

FIG. (5)
SUBJECT (2)

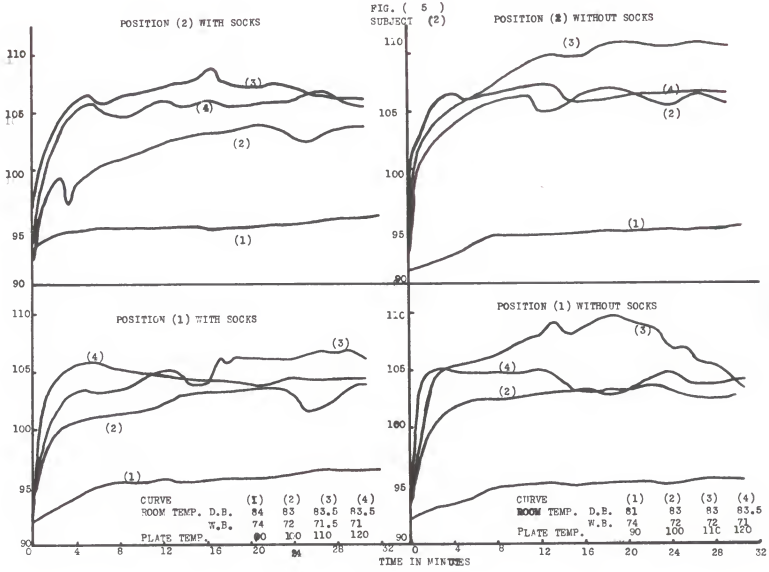


Fig (6)

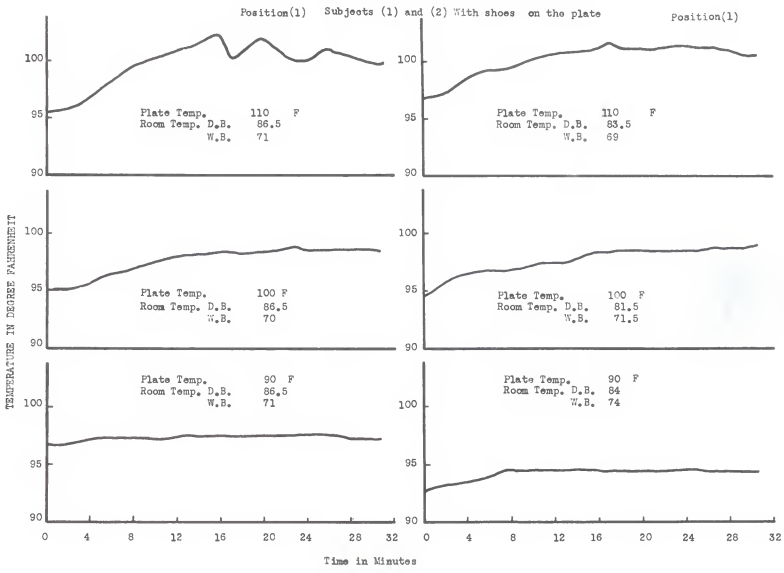

Position(1) Subjects (1) and (2) With shoes on the plate
Position(1)
Plate Temp. 110 F
Room Temp. D.B. 86.5
W.B. 71
Plate Temp. 110 F
Room Temp. D.B. 83.5
W.B. 69
Plate Temp. 100 F
Room Temp. D.B. 86.5
W.B. 70
Plate Temp. 100 F
Room Temp. D.B. 81.5
W.B. 71.5
Plate Temp. 90 F
Room Temp. D.B. 86.5
W.B. 71
Plate Temp. 90 F
Room Temp. D.B. 84
W.B. 74
TEMPERATURE IN DEGREE FAHRENHEIT
100
95
90
0 4 8 12 16 20 24 28 32
Time in Minutes

Fig. (7)

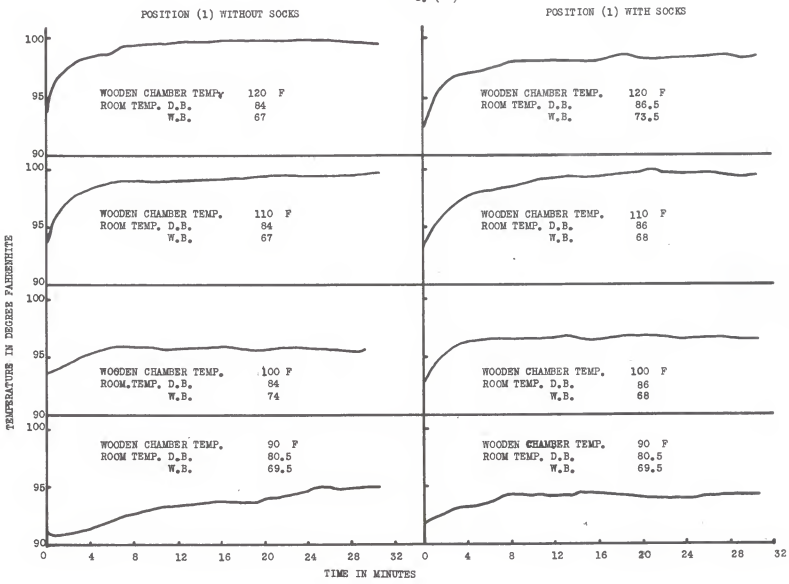

POSITION (1) WITHOUT SOCKS
POSITION (1) WITH SOCKS
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 84
W.B. 67
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 86.5
W.B. 73.5
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 84
W.B. 67
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 86
W.B. 68
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 84
W.B. 74
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 86
W.B. 68
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 80.5
W.B. 69.5
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 80.5
W.B. 69.5
TEMPERATURE IN DEGREE FAHRENHITE
100
95
90
0 4 8 12 16 20 24 28 32
TIME IN MINUTES

FIG. (8)

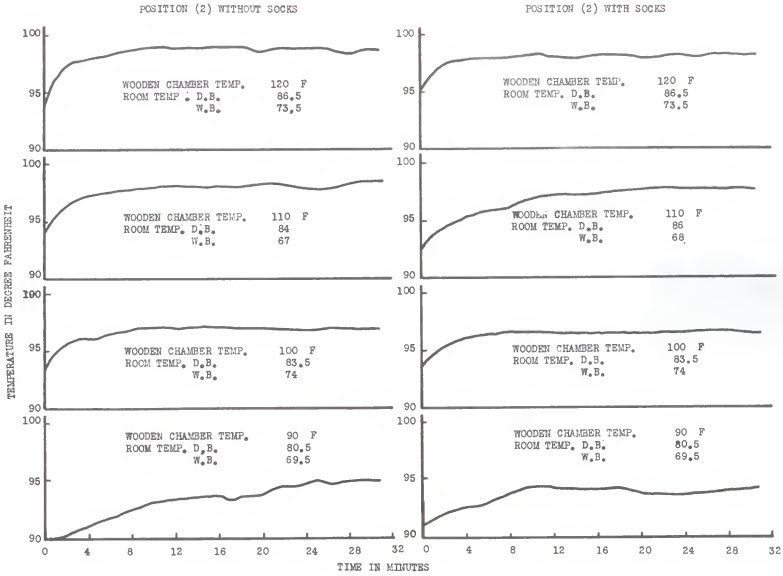

POSITION (2) WITHOUT SOCKS
POSITION (2) WITH SOCKS
TEMPERATURE IN DEGREES FAHRENHEIT
TIME IN MINUTES
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 86.5
W.B. 73.5
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 84
W.B. 67
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 83.5
W.B. 74
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 80.5
W.B. 69.5
100
95
90
0
4
8
12
16
20
24
28
32

FIG. (9)

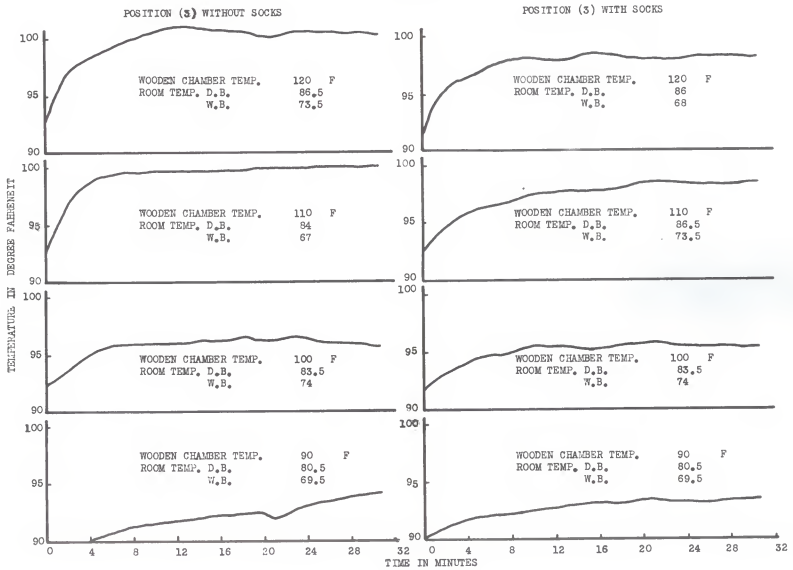

POSITION (5) WITHOUT SOCKS
POSITION (5) WITH SOCKS
TEMPERATURE IN DEGREE FAHRENHEIT
TIME IN MINUTES
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 85.5
W.B. 73.5
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 86
W.B. 68
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 84
W.B. 67
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 86.5
W.B. 73.5
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 83.5
W.B. 74
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 83.5
W.B. 74
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 80.5
W.B. 69.5
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 80.5
W.B. 69.5

FIG. (10)

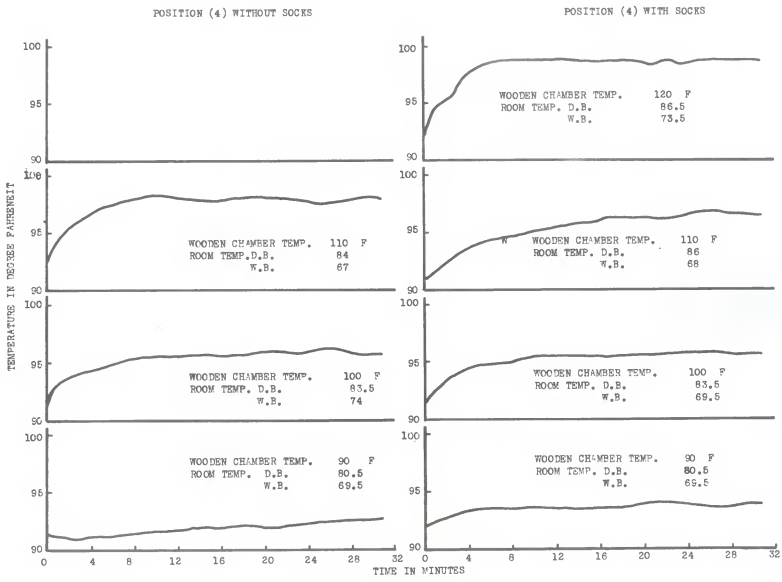

POSITION (4) WITHOUT SOCKS
POSITION (4) WITH SOCKS
TEMPERATURE IN DEGREE FAHRENHEIT
TIME IN MINUTES
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 86.5
W.B. 73.5
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP.D.B. 84
W.B. 67
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 86
W.B. 68
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 83.5
W.B. 74
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 83.5
W.B. 69.5
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 80.5
W.B. 69.5
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 80.5
W.B. 69.5

FIG. (11)

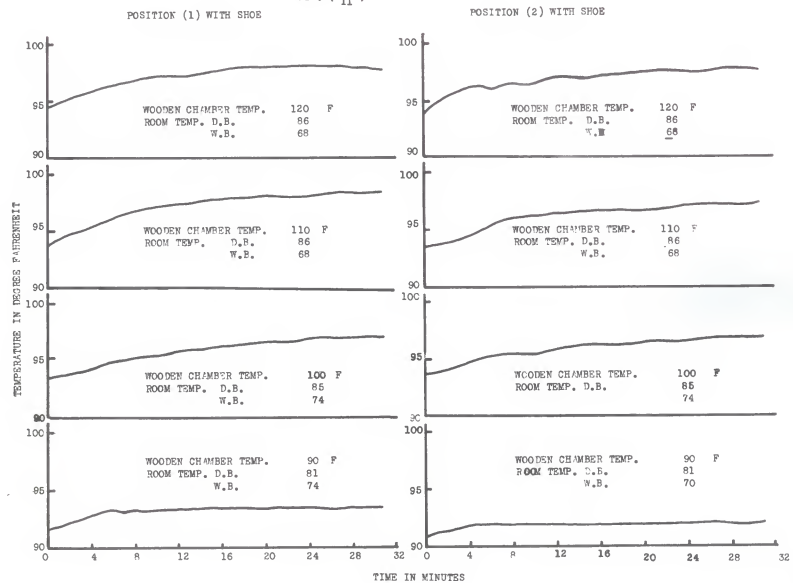
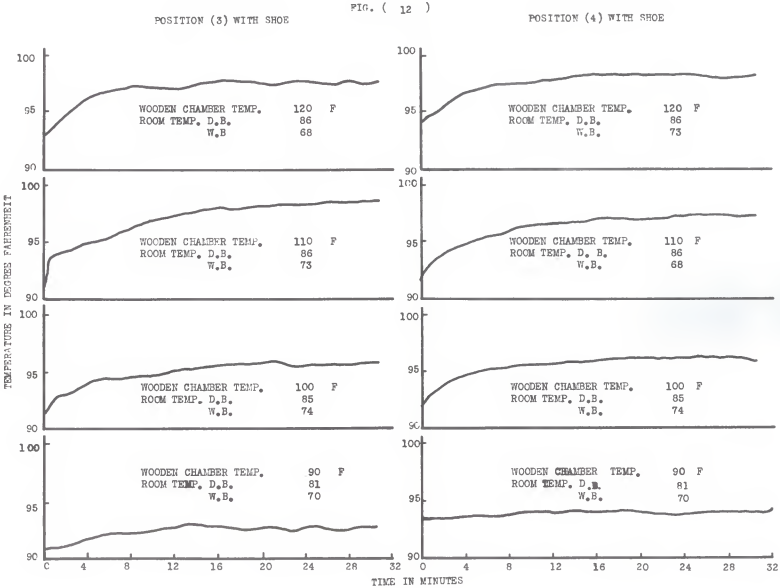

POSITION (1) WITH SHOE
POSITION (2) WITH SHOE
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 86
W.B. 68
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 86
W.B. 68
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 85
W.B. 74
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 81
W.B. 74
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 81
W.B. 70
TEMPERATURE IN DEGREES FAHRENHEIT
100
95
90
0
4
8
12
16
20
24
28
32
TIME IN MINUTES

FIG. (12)


POSITION (3) WITH SHOE
POSITION (4) WITH SHOE
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 86
W.B 68
WOODEN CHAMBER TEMP. 120 F
ROOM TEMP. D.B. 86
W.B. 73
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D.B. 86
W.B. 73
WOODEN CHAMBER TEMP. 110 F
ROOM TEMP. D. B. 86
W.B. 68
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 85
W.B. 74
WOODEN CHAMBER TEMP. 100 F
ROOM TEMP. D.B. 85
W.B. 74
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 81
W.B. 70
WOODEN CHAMBER TEMP. 90 F
ROOM TEMP. D.B. 81
W.B. 70
TEMPERATURE IN DEGREES FAHRENHEIT
100
95
90
0 4 8 12 16 20 24 28 32
TIME IN MINUTES

SOURCES OF ERRORS

1. The skin temperature measurements were subject to a source of error produced by covering the thermocouples and thus reducing the heat loss or gain from the covered area.

2. The thermocouple attached to the foot in the case of the hot plate was affected by the temperature of the plate as well as the foot temperature itself.

3. Since the temperature of the foot varied greatly with the temperature level, the thermocouples might have been representative of one condition but not of the other.

4. The average air temperature of the room was not the same during all the experiments. This may change the heat loss from the subject and consequently the heat loss and temperature of the foot.

DISCUSSION

The results indicate that, in general, the fluctuation of foot temperature exposed to still air is much less than the fluctuation of foot temperature when the foot is in contact with a hot plate. This may be due to the cooling by evaporation which takes place in the first case where the foot perspiration can be evaporated. Also this may indicate a large fluctuation of blood flow in the foot in the second case.

The temperature of the foot changed from one position to another. The heel temperature was higher than the sole temperature. This may be due to the different values of the tissue insulation at these locations.

In the fourth set of the experiments, the subject felt that his toes were warmer than other parts of his foot; presumably this was due to an increase of blood flow in the toe. This also indicates the regulation of heat exchange by the curvature factor.

The wearing of shoes prevents large increases in foot temperature and large fluctuation of this temperature. When wearing shoes, the feet did not feel hot, even when the wooden chamber temperature was increased to 150°F or the plate temperature, increased to 120°F.

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Mechanical Engineering Department

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

The experiments reported here were designed to study the skin temperature response of the foot when exposed to hot environmental conditions.

Skin temperature measurements were made under three conditions (bare, with socks, and with socks and shoes) by placing the foot on a hot plate under various conditions (90, 100, 110, 120°F).

In another experiment, the foot was inserted in a special wooden chamber at various temperature (90, 100, 110, 120°F).

Subjective feelings of warmth and hotness have been reported for various increasing levels of the plate or the chamber temperature while the foot was in contact with the plate or inserted in the chamber.

The foot temperatures were found to increase as the plate or chamber temperature increased. Very large fluctuation of foot skin temperature was observed when the foot was in contact with the hot plate and the hot plate was maintained at temperatures higher than 100°F. Maximum skin temperature attained by the foot was 110°F. Different temperatures have been reported at different positions on the foot at the same moment. The feeling of hotness depends mainly on the skin temperature of the foot and the plate temperature.

The experiments reported here were designed to study the skin temperature response of the foot when exposed to hot environmental conditions.

Skin temperature measurements were made under three conditions (bare, with socks, and with socks and shoes) by placing the foot on a hot plate under various conditions (90, 100, 110, 120°F).

In another experiment, the foot was inserted in a special wooden chamber at various temperature (90, 100, 110, 120°F).

Subjective feelings of warmth and hotness have been reported for various increasing levels of the plate or the chamber temperature while the foot was in contact with the plate or inserted in the chamber.

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